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## THE DESIGN OF HIGH-PERFORMANCE GLIDERS

B. Mueller and V. Heuermann

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16. Abstract A high performance glider is defined as a glider which has been designed to carry the pilot in a minimum of time a given distance, taking into account conditions which are as conveniently as possible. The present investigation has the objective to show approaches for enhancing the cross-country flight cruising speed, giving attention to the difficulties which the design engineer will have to overcome. The characteristics of the cross-country flight and their relation to the cruising speed are discussed, and a description is provided of mathematical expressions concerning the cruising speed, the sinking speed and the optimum gliding speed. The effect of aspect ratio and wing loading on the cruising speed is illustrated with the aid of a graph. Trends in glider development are explored, taking into consideration the design of laminar profiles, the reduction of profile-related drag by plain flaps and the variation of wing loading during the flight.			
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## DESIGN OF HIGH-PERFORMANCE GLIDERS

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## 1. INTRODUCTION

The topic of this lecture is: "Design of high-performance gliders". For a better understanding I would first like to explain in more detail the term "high-performance glider", which is designed to carry the pilot as "conveniently as possible" in a minimum of time a given distance. Here the distance to be covered can be selected by oneself, specified by existing records or by the people directing a contest.

The object of this presentation is to show you how the cross-country cruise speed can be increased and what difficulties arise for the design engineer.

## 2. CROSS-COUNTRY FLIGHT AND CRUISE SPEED

The glide flight is a permanent consequence of ascending flights in upwind and the gliding flights following them (figure 1). For a partial distance  $L$  the time  $t_{st}$  is required for the ascending flight and the time  $t_{gl}$  for the gliding flight, and thus the cruise speed  $V_R$  is

$$V_R = \frac{L}{t_{st} + t_{gl}}$$

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\* Numbers in margin indicate pagination of original foreign text.

If during upwind, altitude is gained by circling with an ascending speed  $w_{st}$  and if  $w_{gl}$  is the sinking speed and  $v_{gl}$  the flight speed during glide, one can also write for the cruise speed

$$V_R = \frac{v_{gl}}{1 + \frac{w_{gl}}{w_{st}}}$$

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Here the climbing speed  $w_{st}$  is the difference between upwind speed  $w_a$  and sinking speed  $w_{sk}$  in circling flight.

$$w_{st} = w_a - w_{sk}$$

A cruise speed as high as possible is achieved if

- the ascending speed  $w_{st}$  is large, or if the sinking speed in circling flight  $w_{sk}$  is small.
- the sinking speed in gliding flight  $w_{gl}$  is small, i.e., if own-weight sinking and air mass sinking are small.
- the gliding flight speed  $v_{gl}$  is large.

In the following it will be shown how the quantities  $w_{st}$ ,  $w_{gl}$ , and  $v_{gl}$  depend on the design quantities of the glider. A consideration of the meteorological conditions is also required particularly in the determination of the ascending speed. To simplify the calculations it is assumed that the air mass is quiescent during the gliding flight and that the pilot is always in a position to fly optimally.

It was already mentioned that the glider gains altitude by circling in upwind whereby a low sinking speed or large ascending speed increases the cruise speed. The sinking speed in circling flight can be calculated from

$$w_{sk} = \frac{c_w}{c_A} \frac{\sqrt{2G}}{S} \frac{1}{[1 - (\frac{2G}{S^2 R})^2]^{3/4}}$$

Thus the sinking speed is the lower the

- lower the area loading  $G/S$
- the greater the circling radius  $R$
- the smaller the ascending factor  $c_W/c_A^{3/2}$ .

For given combinations of area loading and circling drag polars the sinking speeds in circling flights can be plotted against the circle radius. Figure 2 shows the typical curve of sinking speed versus circle radius for different banking positions.

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In order to be able to make any statements concerning the ascending speed, it is naturally necessary to know in addition the upwind speeds as a function of circle radius. Each one of you, who is a glider flyer himself, knows from his own experience that no upwind is identical to the other; there are strong, weak, "round", and "torn" thermals. However, for the design of a glider it is sufficient to use a few basic types of the upwind distribution for the calculations, which allow one to recognize the influence of individual parameters and to make a comparison between different gliders.

The model upwind distributions presented by Carmichael have already been known since the 50's. However, recalculations have shown that these distributions - at least for the central European conditions - do not apply. Therefore Horstmann recommended a few years ago new distributions [1] which conform better to the European conditions. Figure 3 shows the comparison of the model upwind distribution by Carmichael and Horstmann; one can recognize the distinctly lower horizontal upwind gradients in the Horstmann distribution.

The ascending speed is obtained from the difference of upwind speed and sinking speed (figure 4). For each thermal type there thus results an optimum circle radius for the maximum ascending speed. The greater the upwind gradient, the narrower the optimum

circling radius. Figure 5 shows the influence of area loading and aspect ratio on the ascending speed for different upwind gradients. However, it is now not the ascending speed, but the cruise speed which is to be maximized. It is therefore necessary to consider now the gliding flight phase:

To achieve a cruise speed as high as possible, the time span from leaving an upwind at an altitude  $H_0$  up to the regaining of the altitude  $H_0$  must be a minimum. Figure 6 shows the effect of various glide speeds on the cruise speed: /44

Three identical gliders fly simultaneously at an altitude  $H_0$  toward an upwind.

A flies with the best gliding speed. It is the last to reach the upwind, but at the highest possible altitude.

B flies just fast enough to still reach the upwind. If A reaches the upwind at an altitude  $H_A$ , B has already reached the altitude  $H_B$  by circling.

C flies optimally: It reaches the upwind at a higher altitude and later than B and lower and earlier than A. While A and B must still gain altitude by circling, C has already again reached the starting altitude  $H_0$ .

Thus there is an optimum glide speed. It depends on several influence parameters:

$$v_R = v(G/S, 1/3, c_A/c_W, v_{st})$$

Thus the average cruise speed is the greater, the

- greater the area loading
- greater the gliding number
- greater the flight altitude
- greater the ascending speed during circling flight in upwind.

The pilot is now in a position to fly the optimum gliding speed: With the aid of the so-called McCready rings the gliding speed

can be determined as a function of expected ascending speed and actual air mass movement, and the flight speed can be set by appropriate elevator settings.

From the different requirements for ascending- and glide flights there result, in part contradictory requirements for the individual design parameters:

- the area loading must be large for glide flights and small for ascending flights
- for low (glide flight) and high lift coefficients (ascending flight) the profiles must exhibit low drag
- the lift distribution should be elliptical for glide- and ascending flights, that is for distinctly different lift coefficients.

In figure 7 one can see the effect of wing aspect ratio and area loading on the cruise speed. One can recognize that for each thermal type there is an optimum area loading. Since, as already mentioned, there are different meteorological conditions, the area loading should be able to be adapted to the requirements. This is done in practice by taking along water ballast which, however, does not remove all problems:

- one must decide before the flight whether to take along ballast or not
- Although the ballast can be thrown overboard if the conditions get worse, one must then continue to fly with the wrong area loading if the conditions can get better.

Two items are not contained in this theoretical treatment and must be included into the design separately:

- To fly through upwind-free regions (e.g. very high upwind drags) the glider should have the best possible high lift-drag ratio
- As a result of shielding etc. only very weak upwinds can develop for longer periods of time, which no longer make possible any ascending. In order to be able to remain in the air in such

a case for as long as possible - the conditions could again improve and make possible a continuation of the flight - a minimum sinking speed as low as possible is required.

These discussions should serve to demonstrate to you the basic requirements made of a glider. /4

Through an analysis of the glider development till now it becomes possible for the design engineer to recognize meaningful trends for the improvement of the gliders, i.e., in the final analysis to increase the cruise speed.

### 3. TRENDS IN THE GLIDER DEVELOPMENT

The development of gliders is determined to a decisive degree by the three factors-  
aerodynamics  
type of construction  
and flight tactics.

This development is reflected clearly in the flight performances achieved.

With the standard profile (e.g. profiles of Goettingen and NACA fourth- and fifth series) and conventional construction (wood with covering) lift drag ratios of  $E = 30$  were obtained with 15 m wing spread (standard class) and with 20 m wing spread (open class) even values of  $E = 36$ . The area loadings of these machines were near  $m/S \approx 20 \text{ kg/m}^2$ , whereby small minimum sinking speeds were reached under simultaneously poor glide performances in high-speed flight.

With the development of the laminar profiles, which exhibit low drag in large  $c_a$ -ranges, i.e. broad laminar low depressions, a distinct performance increase was achieved.



E = 41 for standard class gliders and

E = 57 for gliders of the open class

are at present the peak values. For a successful utilization of these profiles, however, high demands had to be made of the dimensional accuracy and surface quality of the wings. By the use of the material GFK (fiberglass reinforced plastic) in conjunction with the negative construction mode the required dimensional accuracies could be achieved for low structural weights.

In this place let us mention the fs 24 "Phoenix" of the Academic Flying Group Stuttgart, the first GFK glider with laminar profile, which was already flying in 1957 and could exhibit the impressive lift drag ratio of E = 40 for a 16 m wing spread. /47

Since the laminar profiles exhibit low drags especially for high lift coefficients, it was possible together with the GFK construction mode to increase the aspect ratios and area loading, which significantly improved the glider performances and nevertheless made possible good ascension. Aspect ratios of  $\lambda = 20$  at 15 m and  $\lambda \sim 36$  at 20 m wing spread for area loadings of  $m/S \sim 30 \text{ kg/m}^2$  were able to prevail.

The SB 6 and SB 7 of the Academic Flying Group Brunswick and the BS 1 developed from the SB 6, which made their initial flight in the years 1961/1962, are important milestones in the development of the high-performance gliders.

By the use of so-called curved flaps (trailing edge flaps) the profile drag was again reduced: The shifting of smaller, lower-drag laminar depressions with the curved flap positioning made possible an adaptation of the profile to the requirements in slow- and high-speed flight. The effect of the curved flap on the drag polars in comparison to rigid profiles can be seen from figure 8. However, the utilization of the curved flap profiles is limited to the open and the FAI-15 m class because of the class regulations. Figure 9 shows the improvement of the flight performances resulting from the improved aerodynamics.

The forward step of decisive importance in this connection was made with the D 36 of the Academic Flying Group Darmstadt. With a wing spread of barely 18 m flight performances were achieved here already in 1964, which could not be surpassed with production machines until 1970. By means of increases in wing spread and aspect ratio additional performance increases could be achieved: SB 9, minibus, ASW 17 and H 604, gliders with 20 ... 22 m wing spread, reached lift-drag ratios of approximately  $E \approx 50$  and minimum sinking speed of 0.5 m/s.

New dimensions were possible with the material CFK (carbon fiber reinforced plastic): in 1972 the SB 10, a high-performance twin-seater with 26/29 m wing spread and the aspect ratio of  $1=36$ , not reached till then, rose into the air. With a lift-drag ratio of 53 and pleasant flight properties the goal of this design was achieved. /48

It was not until 1981 that these orders of magnitude were again achieved with production machines. 24.5 m wing spread and aspect ratios of barely 40 lead, together with the new profiles and the CFK construction mode, to lift-drag ratios of 57 and minimum sinking speeds of 0.42 m/s; "flooding" seems to be almost impossible with such performances.

The use of water ballast, which started to prevail already shortly after the introduction of the mass production of GFK gliders, makes possible an adaptation to different weather conditions: During strong thermals high area loadings were used for flying, whereby the advantages in high-speed flight outweigh the disadvantages in slow flight. During weak thermals the water is thrown overboard or not used at all, whereby the better ascending performances of the light-weight machine can be utilized.

The variation in area loading through water ballast has been continuously promoted in the glider development. The reasons for this are:

- improvement in the profiling (laminar depressions widened in an upward direction)
- reduction of the equipped weight (empty weight plus fixed weight) through improved construction techniques (e.g. replacement of GFK by CFK)
- improvement in the flying tactics, through which the time portion of circling in upwind is reduced (e.g. by utilizing upwind sequences).

However, an adaptation to the weather is possible only once and in one direction, i.e., if the water has been jettisoned because of poor thermals, one must also continue the flight with the poorer high-speed performance if good thermals are again encountered.

This problem led to the demand for area loadings that could be changed during flight. As a possible solution for this we list the variable geometry, i.e. area changes during flight with respect to wing spread (telescoping wing) or with respect to chords (Fowler-, area flap wing): During slow flight one flies with low, during high-speed flight with high area loading. /40

The decision, which concept should be preferred, the telescopic wing or the area flap wing, proved to be in favor of the wing flaps as the result of comparative performance calculations: The adaptation to the high speed- and slow speed flight only with the aid of changes of wing areas and wing spread did not reach the performances achieved by changes in curvature and wing area for wing-flap wings.

In the last few years different gliders were constructed with variable geometries, such as the fs 29 of the Akaflieg Stuttgart, the until now only glider with telescopic wings, and several gliders with wing flaps: Sigma, AN 66C, SB 11, Delfin I and II, MÜ 27, M-2. In spite of the large constructional and financial expenditures most of the machines did not enjoy any success. Only the SB 11

of the Akaflieg Braunschweig was able to achieve a spectacular success in the FAI-15 m class during the world championship in 1978 which, however, could not be repeated in a similar manner. Together with the required high structural expenditures this could probably be the cause why a mass production of gliders with wing flaps has not taken place till now.

Of interest is a comparison of the speed polars of different gliders of one class. Here the FAI-15 m class offers itself since equal wing spreads are prescribed, but otherwise no construction limitations are imposed on the designer. In order to be able to make comparisons, the gliders ASW 20, SB 11, and Ventus A. were chosen. The ASW 20 represents in my opinion the highest performance racing class glider of the older generation (1975) and the Ventus A that of the more recent generation (1980). For comparison we use the SB 11 which is not only the most successful glider with wing flaps, but which also makes possible because of its design interesting conclusions for the design of future gliders. /50

One can recognize in figure 10 that the SB11, compared to the ASW 20 and Ventus A, possesses a distinctly lower minimum course and higher minimum sinking speed. The Ventus, on the other hand, possesses good glide performances for moderate speeds. The explanation for these quite different polars lies, among others, in the cross-country flight models on which the designs are based: Older designs (SB 11) start with the idea that altitude is gained in upwind by circling and that the gliding flight between the upwinds occurs on the average in quiescent air. In particular the SB 11 was designed for the idea to obtain flying advantages during circling in upwinds of the "Horstmann type". However, except for very narrow thermals these advantages are small in practice, or for weak thermals a certain inferiority even prevails. Since this was not to be expected in performance calculations - the greater sinking can be compensated through narrower circles - interesting aspects result from the experiences with the SB 11 for the design engineer:

- The cross-country flight model needs revising.
- Neglecting the flight properties in favor of the flight performances can lead to the fact that the theoretically possible advantages cannot be obtained in flight.
- Small performance-related inferiority in individual items in favor of distinct superiority in other items can lead altogether to substantial disadvantages.

Although modern cross-country flying tactics include as before circling in upwind and subsequent gliding flight, the circling flight portions become ever smaller: Naturally the gliding flight can be extended substantially if flying takes place instead of in quiescent air in on the average ascending air masses. The extended gliding flight additionally offers the possibility to utilize individually encountered especially good upwinds, whereby ascending time in circling flight can still be reduced further. (E. G. Petep reports /51 about circling flight percentages from a time standpoint of only 20% in some cross-country flights).

However, flight in ascending air again means that one must fly with lower speeds than in quiet air. From this it follows that the velocity polars in the moderate speed range - from the best gliding up to 150...160 km/h - should be especially good. If the water ballast is taken along, this range is shifted to correspondingly higher speeds. This trend becomes pronounced during the comparison of ASW 20 and Ventus A.

Narrower circles necessarily include low circling flight speeds. These lead to lower maneuverability which makes difficult optimum "cranking". Therefore with decreasing circle radius, especially if one is flying with lift-drag ratios, a more unfavorable uplift distribution prevails: The narrower the circle, the greater is the required local lift-drag ratio at the inner circle wing end. This leads to

- the well known effect of tumbling down, which reduces the maneuverability by the fact that less aileron deflection is available for stabilizing or shifting.
- to the fact that the  $c_{amax}$  is first reached at the circle-interior wing end. However, since the remaining wing still possesses  $c_a$ -reserves, this means that the  $c_{Amax}$  reached in straight-line flight is not attained. Since this effect increases with increasing  $c_A$ , this means that the method, to draw conclusions from the straight-line flight polars to the circular-flight polars, always leads to "more wrong" results with increasing  $c_{Amax}$  and that finally the expected performance is always obtained less and less.

#### 4. EFFECT ON THE DESIGN

It was shown till now that by means of mathematical models an optimization of the cruise speed is principally possible, but that additional boundary conditions bring about a shift of the optimum. In the following I would like to present starting points for improvement, whereby no claim is made for completeness.

Independently of weather models a general possibility for the improvement of the flight performances is the reduction of the drag for a given flight range and equipped weight (improvement of an existing glider). Here one must consider on the one hand the reduction of the profile drag and on the other hand the reduction of fuselage-, empennage-, and interference drag. /52

With respect to the reduction in profile drag Messrs. Horstmann and Quast will present detailed discussions during the further course of the symposium.

Various measurements on fuselage models [2], [3] allow one to expect, through suitable shaping for constant fuselage cross-sectional area up to 25%, savings in fuselage drag compared to conventional fuselages.

At present an especially radical step for drag reduction is made by the Academic Flying Group: Since one can develop from the modern rigid profiles without significant loss in  $c_{amax}$  for equal drag constant center of pressure profile, the concept of the tail-less glider (all wing), no longer pursued for decades, was revised. If pleasant flight properties are possible for such a configuration, the tail-less glider could represent a real alternative for the at present standard-class gliders.

Performance increases are also possible by means of profiles with wider laminar depressions, even then when these profiles produce somewhat higher drags: By means of increases in aspect ratio one can reduce induced and harmful empennage drags. Typical representatives of this concept are the above-named gliders with wing flaps. Because of the higher lift-drag ratios one must pay particular attention here to the circling flight properties since otherwise, as mentioned, the potentially appearing advantages cannot be utilized for flight.

An additional possibility for performance increases is represented by the wing spread- and aspect ratio increase - permitted only in the open class.

The limits of that which can be achieved are set not only for the case of the wide laminar depressions, but also for increases in wing spread primarily by flight properties: In both cases there results not only a loss in maneuverability, but also the properties in stationary circling flight become worse. L

I should like to demonstrate with the aid of a few results of the calculations carried out by me for the lift-drag ratio distributions in circling flight how the circling flight properties - and thus in the end also the flight performances - can be improved. Although these results present no significant enlargement of the knowledge concerning the aerodynamics in circling flight, they

do give to the designer the possibility to achieve improvements through specific measures.

If the possible maximum lift-drag coefficient  $c_{amax}$  is constant over the wing spread, this means that the wing - except at the circle-interior wing end - is far removed from  $c_{amax}$ . The  $c_{Amax}$  of the straight-line flight is not reached, the stalling properties are unpleasant (smearing). By means of super-elliptical wing area distribution in the outer wing and/or twisting or, in my opinion, rather by suitable profiling, one must make sure that the inner wing first reaches the  $c_{amax}$ , which leads to better utilization of the wing and thus to lower drag and better flight properties.

Additionally the shape of the lift increase in the outer wing should possess no "danglers". In this way tumbling movements during wind squalls (torn thermals), which make more difficult a coordination of glider movements with air mass movements, are avoided.

High aileron differentiations have a favorable effect in circling flights. However, degressive force gradients are possible here. For gliders with curved flaps one can achieve through low differentiation of the inner aileron (curved flap) not only a nearly arbitrary force gradient, but one can additionally achieve

- lower k-factors (more favorable lift distribution)
- low or none whatsoever  $c_A$ -losses, as they would otherwise occur through curvature loss for high differentiations.

In conclusion, I would like to show to you in this place the comparison of a relative unfavorable configuration and a favorable one in my opinion (figure 11):

The "ideal configuration" is not only in a position to fly with lower profile- $c_{amax}$  and thus lower drag, but also possesses still more pleasant flight properties such as favorable stall properties and "sense of thermals".



I hope to have presented to you with this lecture insight into the possibilities and difficulties of glider design and thank you for your attention.

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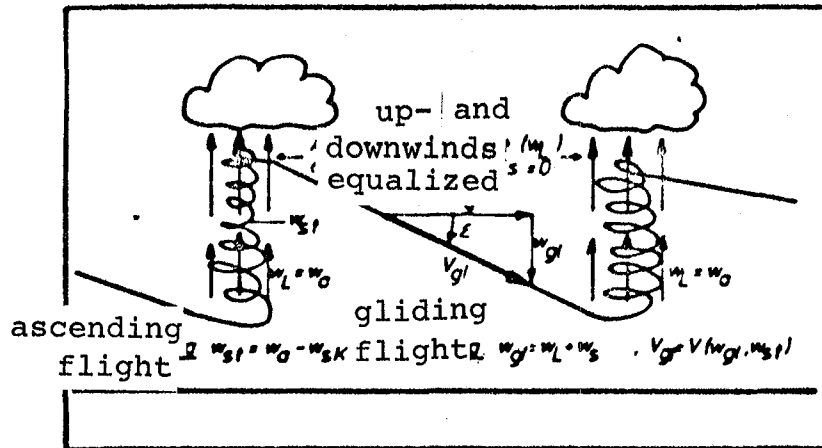


Figure 1: Idealized cross-country flight model

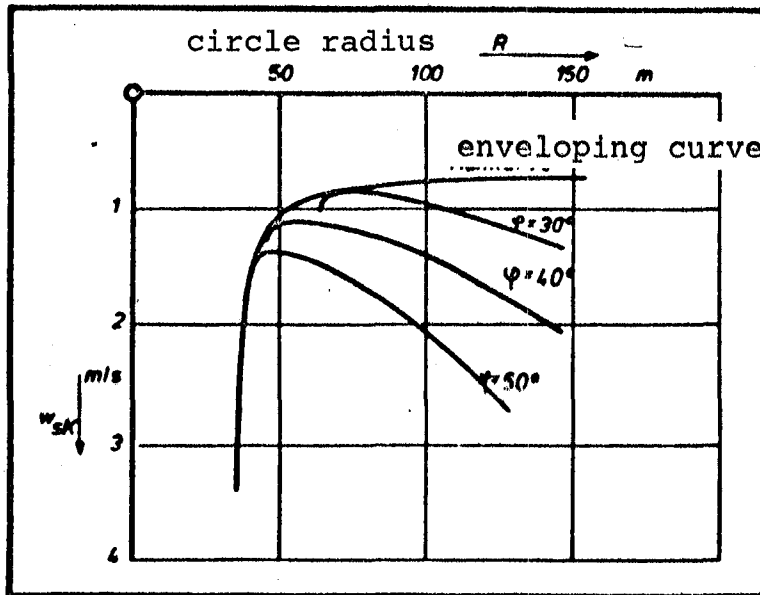


Figure 2: Sinking speed in circling flight as a function of circle radius and banking position

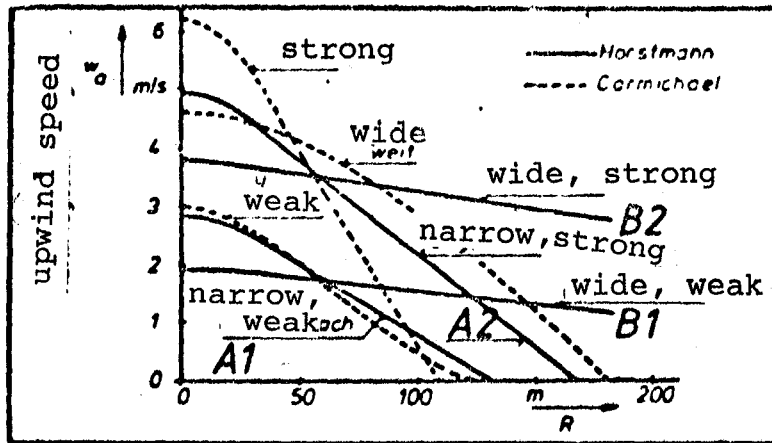


Figure 3: Comparison of the model upwind distributions according to Carmichael and Horstmann

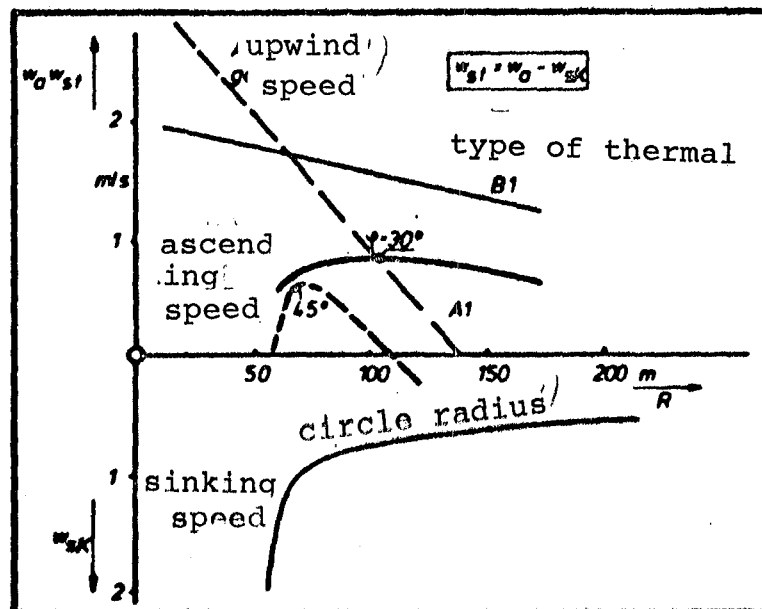
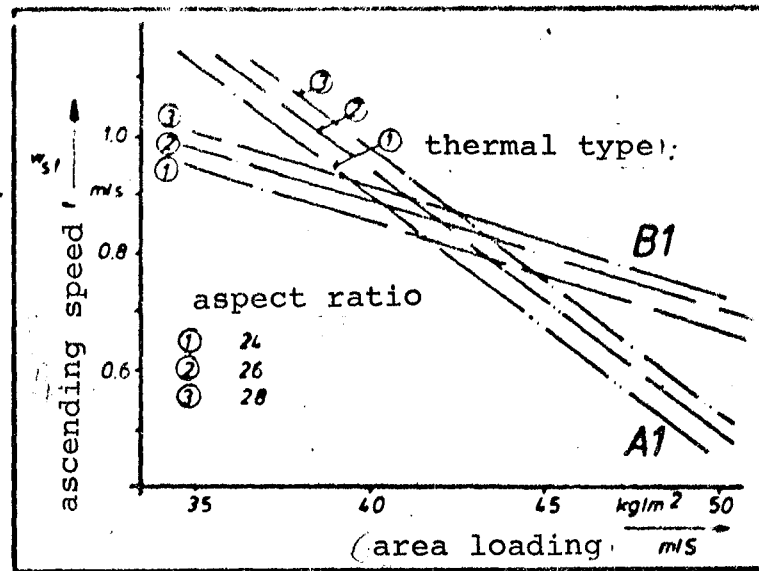
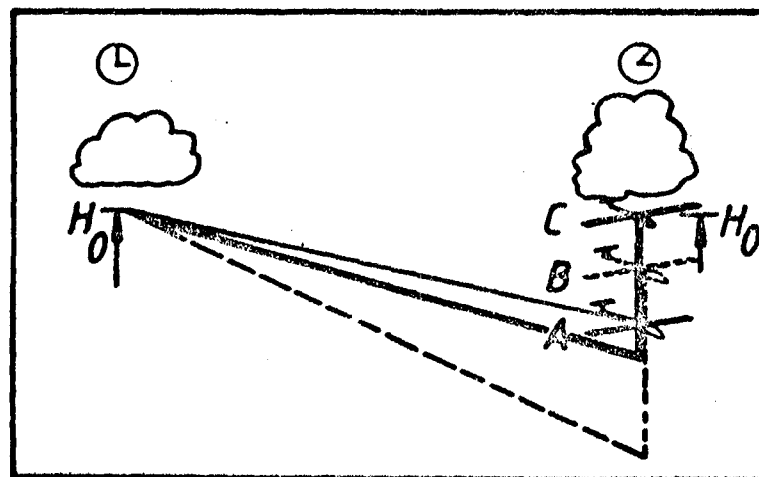


Figure 4: Sinking speed for different upwind gradients and circle radii



Ascending speeds as a function of area loading and aspect ratio for equal wing spread and profiling



Concerning the optimum gliding flight speed

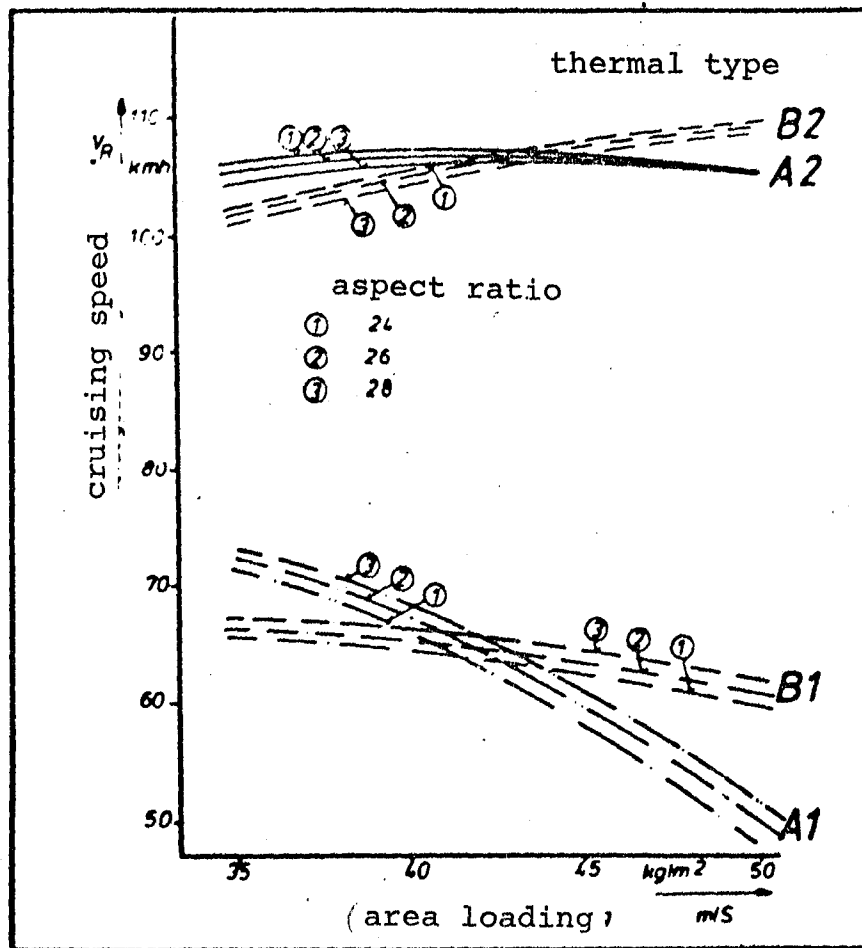


Figure 7: Cruising speeds as a function of area loading and aspect ratio for different thermal types of Horstmann (equal wing spread and profile)

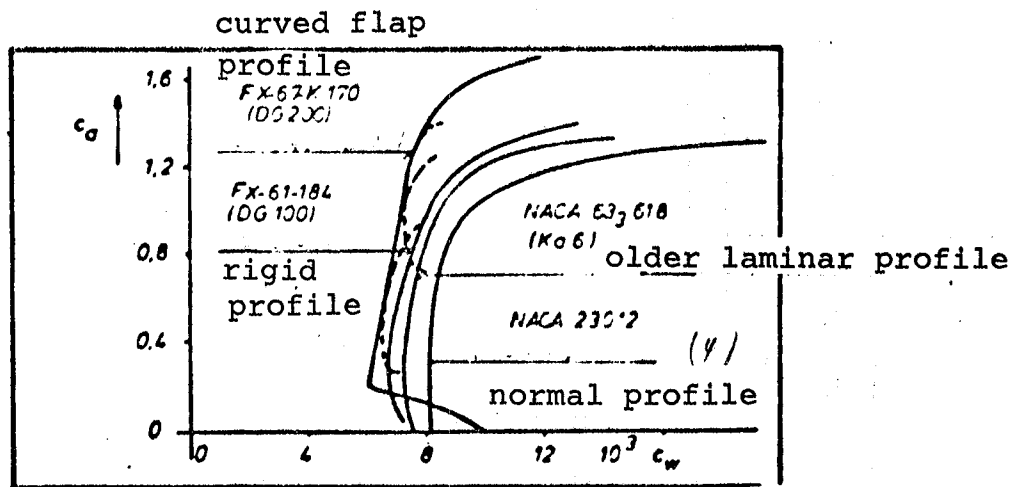


Figure 8: Comparison of different profiles for gliders at  $Re=1.5 \cdot 10^6$

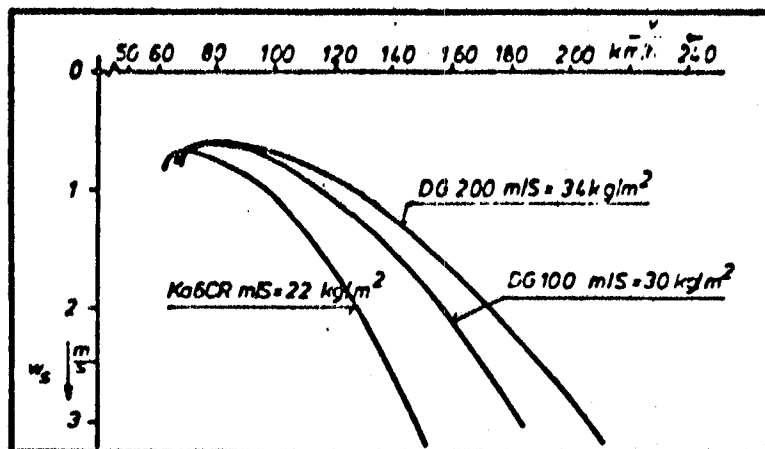


Figure 9: Comparison of the speed polars for different gliders with 15m wing spread and typical area loadings

Ka 6CR: standard class, wood construction mode

DG 100: standard class, GFK-construction mode

DG 200: FAI-15m-class, GFK construction mode

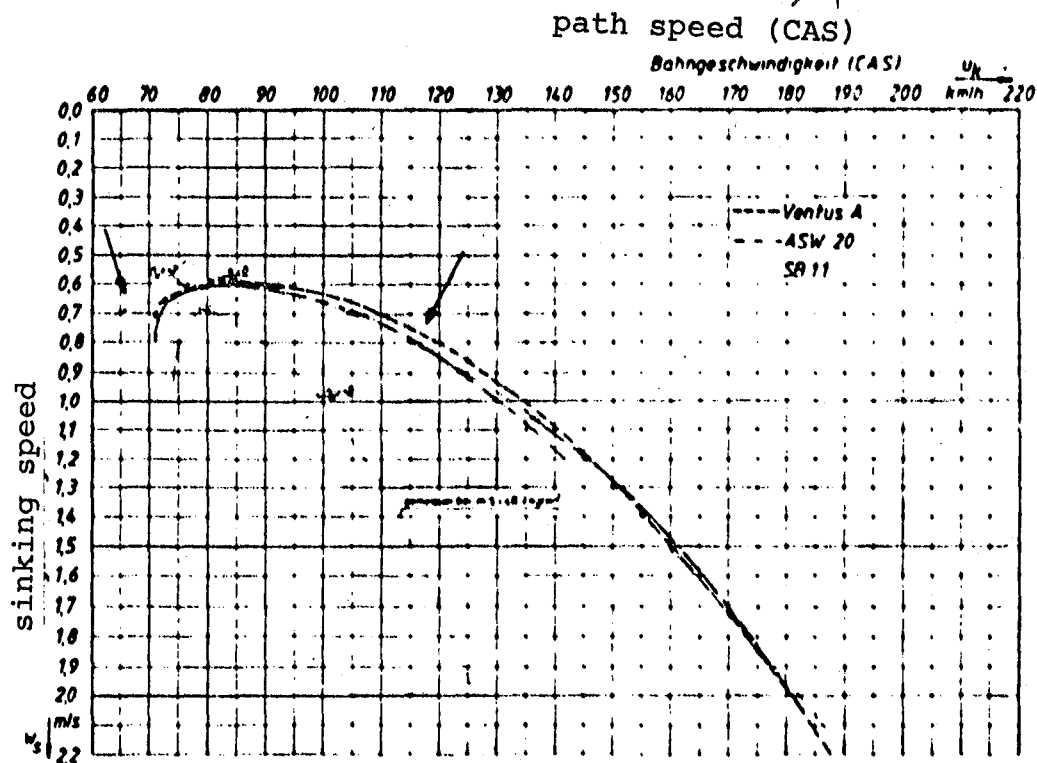
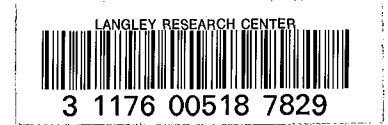


Figure 10: Speed polars of Ventus A D-7072 m/S=35kg/m<sup>2</sup>  
 ASW 20 D=7476 m/S=33.6kg/m<sup>2</sup> from comparison flights  
 4 SB11 D-1177 m/S=36.9kg/m<sup>2</sup> (FKout recalculated to  
 36.9kg/m<sup>2</sup>)

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